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Stress Rupture Properties of 316L(N) Stainless Steel under the Influence of Multiaxiality at Various Stress Levels

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Abstract

Type 316 L (N) stainless steel is one of the construction materials for Pressurized Fast Breeder Reactor, in India. The design of a material part involves various types of geometrical irregularities such as notches, holes, etc. which impose a certain degree of constraint on the deformation. The present work aims to couple one such mechanical constraint with the metallurgical changes that occur during creep. Multiaxiality is generated following the mechanical route, by machining a circumferential 60 ^{0} V-notch. This study not only represents the case of threaded portions, but is also used for observing the notch strengthening or weakening behavior. Stress rupture curve was generated for 316L(N) SS tested at 923 K and the fractographs were explained qualitatively with multiaxial stress parameters.

Keywords: Creep; 316 LN SS; multiaxiality; fracture

1. Introduction

The operating temperature for the existing nuclear reactors in the world is ~823 K, where particular attention must be given to a high temperature phenomenon called creep. Compared to deformation at room temperature, high temperature deformation is more complex and involves multiple mechanisms that lead to rupture.

At low temperatures, dislocations glide on slip planes, and the dominant mechanisms include the overcoming of the Peierls barriers by the nucleation and propagation of a pair of kinks or the overcoming of obstacles such as precipitate particles by a bowing process. At high temperatures, (T> 0.4T_m), diffusion occurs rapidly. Dislocations acquire a new degree of freedom in their motion, and edge dislocations are no longer constrained to glide exclusively on their original slip planes or are held up at obstacles. Instead, vacancies diffuse to the edge components of dislocations resulting climb of dislocations to new slip planes on which they glide further producing large strain [1]. Work hardening and recovery occur during the primary and secondary stages of creep. The balance between these processes gives rise to the steady state creep rate (observed in the

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secondary stage). Finally, more complex phenomenon like multiple cross-slip occurs leading to the rupture of the material.

Engineering structures operating at elevated temperatures essentially involve multiaxial stress states at locations such as welded joints, bends, changes in cross section etc. Laboratory creep test specimens are designed to simulate multiaxiality of stress to assess the life under multiaxiality so as to predict the actual material behavior in service [2]. V- Notched specimens are originally designed to represent the stress states developed at thread roots. In practice, standard V- notched test pieces are employed as a means of characterizing notch strengthening or notch weakening behavior in materials used for a wide range of high temperature applications[3]. The parameters used to describe multi-axial stress states are Von Mises' equivalent stress σ_{vm}, mean stress σ_m, maximum principal stress σ_1, and stress triaxiality σ_m / σ_{vm} [4].

2. Material

316 L (N) belongs to the category of Austenitic stainless steels where 3xxx denotes Nickel- Chromium series. The composition of 316 L (N) stainless steel is given in table 1. To avoid sensitization, carbon content is lowered in this steel to 0.03 wt%. Addition of nitrogen facilitates solid solution strengthening, thereby, compensating the loss in strength due to the decrease in C content. Extensive high temperature deformation studies on this material indicate that the presence of nitrogen reduces the diffusivity of chromium in austenitic stainless steels, thereby, retarding the coarsening of $M_{23}C_6$ carbides in these steels. Thus, the beneficial effects of carbide precipitation are retained to longer times in steels containing N. Further, the precipitation of nitrides is not expected at the temperatures employed in this study. Thus, coarsening of carbides is delayed and their efficiency to strengthen the grain boundaries is maintained for a longer period. It is established that 316 L (N) SS exhibited better resistance to creep deformation compared to their 316 SS counterparts when tested in the range of stresses 100 to 335 MPa at 873 and 923 K [5].

Table 1. Composition (wt %) of the test material 316 L (N) SS.

Cr	C	Ni	Mo	Mn	Si	S	P	Cu	B	N
17.12	0.023	12.21	2.31	1.65	0.29	0.003	0.024	0.10	0.0012	0.086

3. Experimental work

In the present work, uniaxial tensile stress rupture tests were performed. Stress multiaxiality was introduced by having 60 ^{0} V-notch in the samples. The dimensional details are provided in Fig. 1. The initial elastic stress concentration factor (K_t) calculated considering only the notch geometry was 4.1 [6]. The tests were carried out at 923 K. The stress level was varied from 216 to 325 MPa. The samples were coded based on the stress level. Stress rupture tests were performed according to the ASTM standards E139 and E602. The resultant fractographs were observed in top-view and the micrographs were taken in the longitudinal direction.

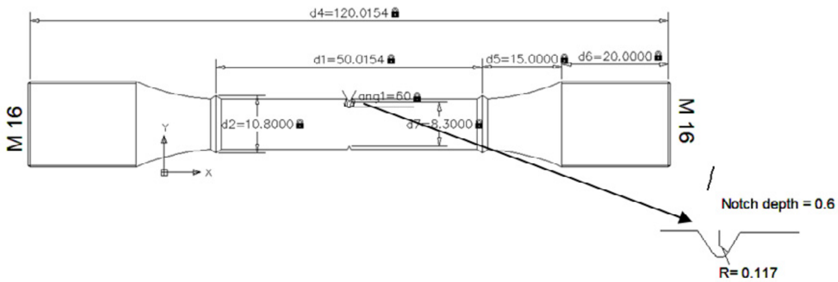


Fig. 1. Dimensions of the test sample (All dimensions are in mm).

4. Results and discussion

4.1. Stress rupture curve

The rupure lives obtained for the samples are shown in table 2. Rupture life was found to increase with decrease in stress level. However, the Stress Rupture curve plotted (Fig.2) gives us an indication of the change of slope which can be used as an indication of the extent of extrapolation for samples with same K_t operating under similar conditions.

Table.2. Sample nomenclature and rupture lives

Sample Nomenclature	Notch depth (mm)	Notch root radius (mm)	Stress level (MPa)	Rupture time (hrs.)
P-325	0.6	0.117	325	21
P-300	0.6	0.117	300	87
P-275	0.6	0.117	275	580
P-245	0.6	0.117	245	2310
P-216	0.6	0.117	216	5365

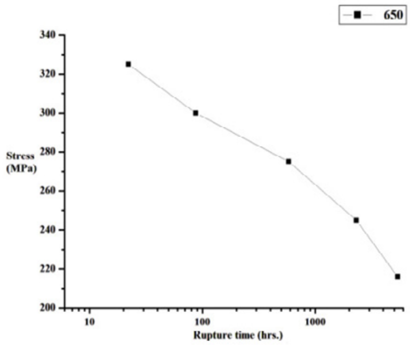


Fig. 2. Stress rupture curve.

4.2. Fractography

For each specimen the fracture surface was observed at selected locations R1 to R3 from the notch root as indicated in fig.3. The selection of these locations is on the basis of variations in the stress developed during deformation which is highest at the notch root and decreases towards the center. All the specimens showed mixed mode of fracture, while the area fraction of brittle and ductile portions varied.

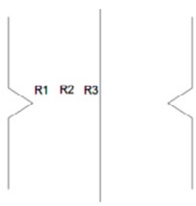
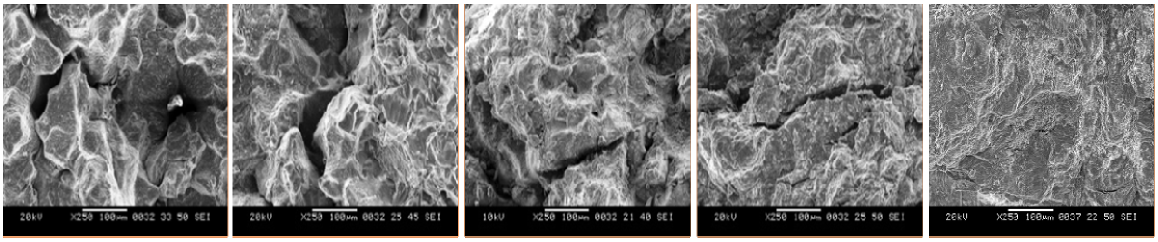


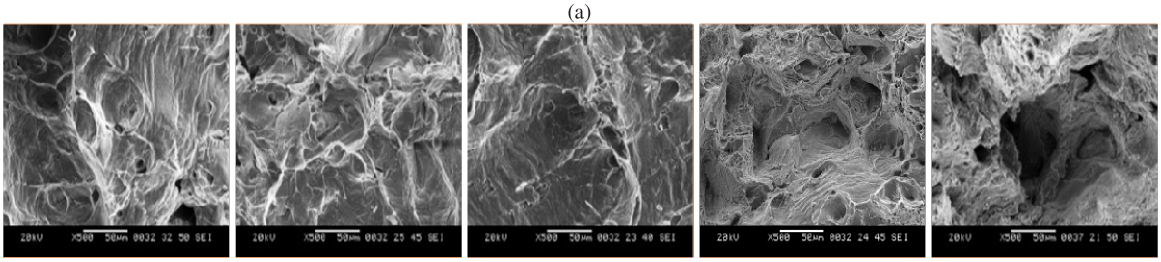
Fig. 3. Different regions of the specimen.

The notch creates a triaxial state of stress, and the specimen is very much constrained to deform. The degree of constraint varies with notch geometry. In the present case of identical geometries, the quantification of stress levels at different points away from the notch root decides the brittle and ductile modes of fracture. All the specimens tested here indicated dominance of brittle fracture at location R1 with highest stress level. Transition from ductile to brittle was observed in mixed mode fracture at location R2 having intermediate stress level, while R3 showed mostly ductile fracture features. The constraint imposed on the plastic deformation of the material slows the deformation and thereby, the material lasts longer in the elastic region. As a result when the stress concentration developed becomes sufficiently intense that a crack is originated at that point (notch is a source of crack). However, from the basic design of the notch, it is obvious that the stress which peaks at the notch root gradually softens on moving towards the center, reducing the constraint. Once this constraint is reduced, the material deforms plastically where the crack has to propagate in plastic region causing the ductile fracture at R3.

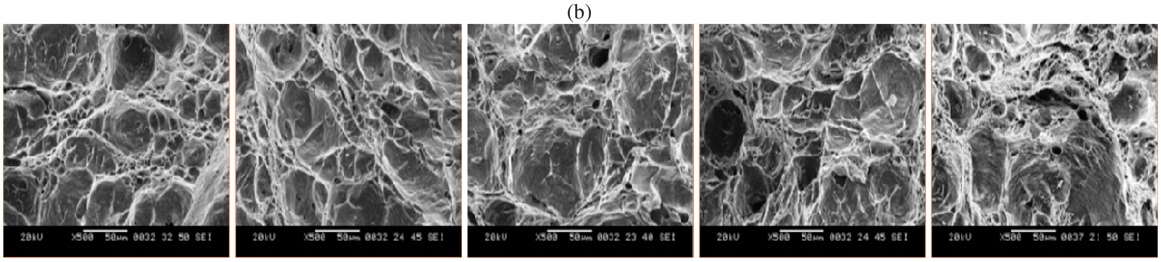
The fractographs for the locations R1, R2, and R3 for all the specimens are shown in fig.4. For comparison of the effect of imposed stress varying from 325 to 216 MPa, R1 of each specimen is indicated in fig.4(a), R2 in 4(b) and R3 in 4(c). Li Bin Nu et al. [4] reported that, while the von Mises equivalent stress σ_{vm} is responsible for the nucleation of cavities, the mean stress σ_m is responsible for the growth of cavities. At the notch root, σ_{vm} is large compared to σ_m. More cavities are nucleated with less growth giving the appearance of facets (brittle) (fig.4(a)). The transition region R2 is denoted where it contains intermediate values of σ_{vm} and σ_m (fig. 4(b)). At the center, σ_{vm} is less compared to σ_m, which means the cavities even though, nucleated in less numbers, grow more, causing dimples (ductile) (fig.4 (c)). At high stresses, the intense stress concentration causes the facets to be more distinct. Also, at high stresses, stress is redistributed over a larger area, which accounts for greater fraction of brittle fracture. At R3, it would be in plastic deformation zone where a reduced cross section has to bear the load (increased stress) which leads to the fracture. The high stresses do not allow cavities to coalesce and the material gets tore, showing ligaments. The converse of above is true at lower stresses.



(a)



(b)



(c)

Fig. 4. (a) R1 regions of P-325, P-300, P-275, P-245, P-216 (from left to right), (b) R2 regions of P-325, P-300, P-275, P-245, P-216, (c) R3 regions of P-325, P-300, P-275, P-245, P-216.

The above interpretation is purely on the basis of mechanical constraint. Due to creep, precipitations of carbides occur along the grain boundaries (fig.5) which can be characterized by EDS. The higher stress levels prevent the $M_{23}C_6$ carbides to precipitate along the grain boundaries resulting fracture in shorter time. At lower stresses however, material is exposed to high temperature for longer time. The initial precipitates which were fine coarsen later and act as cavity nucleation sites.

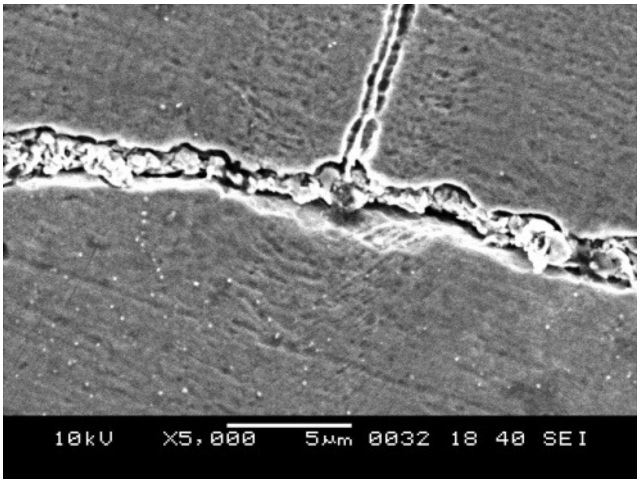


Fig. 5. Grain boundary precipitation of carbides.

5. Conclusions

The study indicates that multiaxiality of stress developed during high temperature deformation changes the deformation mode as influenced by the level of stresses developed. Careful fractography of the samples further establishes the dominant mode of fracture which is brittle for highest stress level at the notch root and ductile at the center with transition at intermediate level. The area fractions of brittle and ductile fracture obtained for the test stresses help in design of the material part.

Acknowledgements

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